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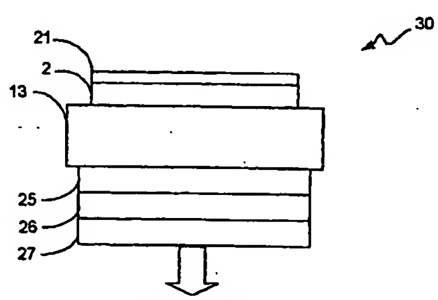
(54) Title: A LIGHT EMITTING DIODE DEVICE THAT PRODUCES WHITE LIGHT BY PERFORMING COMPLETE PHOSPHOR CONVERSION



(57) Abstract: The present invention provides an LED device that performs phosphor conversion on substantially all of the primary light emitted by the light emitting structure of the LED device to produce white light. The LED device comprises at least one phosphor-converting element located to receive and absorb substantially all of the primary light emitted by the light-emitting structure. The phosphor-converting element emits secondary light at second and third wavelengths that combine to produce white light. The second wavelength is greater than the first wavelength and the third wavelength is greater than the second wavelength. The phosphor-converting element generates the secondary light at the third wavelength in response to excitation by the primary light and/or the secondary light at the second wavelength. The excitation by the secondary light at the second wavelength is effected by macroscopic absorption and/or quantum-mechanical transfer. The phosphor-converting element includes either (a) a first host material doped with a first dopant and a second host material doped with a second dopant, or (b) a host material doped with a first dopant and a second dopant. The first dopant emits the secondary light at the second wavelength and the second dopant emits the secondary light at the third wavelength. Additional host materials may be included in the phosphor-converting element, or additional phosphor-converting elements may be included in the LED device, that produce additional wavelengths of secondary light that combine with the second and third wavelengths of secondary light to produce white light.

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

A LIGHT EMITTING DIODE DEVICE THAT PRODUCES WHITE LIGHT BY PERFORMING COMPLETE PHOSPHOR CONVERSION

TECHNICAL FIELD OF THE INVENTION

The present invention relates to light emitting diode (LED) devices and, more particularly, to an LED device that performs phosphor conversion on all of the primary radiation emitted by the light emitting structure of the LED device to produce white light.

BACKGROUND OF THE INVENTION

With the development of efficient LED devices that emit blue or ultraviolet (UV) light, it has become feasible to produce LED devices that generate white light through phosphor conversion of a portion of the primary radiation emission of the light emitting structure of the LED device to longer wavelengths. Conversion of primary emission to longer wavelengths is commonly referred to as down-conversion of the primary emission. An unconverted portion of the primary emission combines with the light of longer wavelength to produce white light. LED devices that produce white light through phosphor conversion are useful for signaling and illumination purposes. LED devices having light emitting structures that emit white light directly currently do not exist.

Currently, state-of-the-art phosphor conversion of a portion of the primary emission of the LED devices is attained by placing phosphors in an epoxy that is used to fill a reflector cup, which houses the LED device within the LED lamp. The phosphor is comprised as a powder that is mixed into the epoxy prior to curing the epoxy. The uncured epoxy slurry containing the phosphor powder is then deposited onto the LED device and is subsequently cured.

The phosphor particles within the cured epoxy generally are randomly oriented and interspersed throughout the epoxy. A portion of the primary light emitted by the LED device passes through the epoxy without impinging on the phosphor particles, whereas a portion of the primary light emitted by the LED device impinges on the phosphor particles, thereby causing the phosphor particles to emit yellow light. The combination of the primary blue light and the phosphor-emitted yellow light produces white light.

One disadvantage of using phosphor-converting epoxy in this manner is that uniformity in the white light emitted by the LED device is difficult, if not impossible, to obtain. This non-uniformity is caused by non-uniformity in the sizes of the phosphor particles mixed into the epoxy slurry. Currently, phosphor powders having uniform phosphor particle sizes generally are not available. When the phosphor powder is mixed into the epoxy slurry, the larger phosphor particles sink faster than the smaller phosphor particles. This non-uniformity in spatial distribution of the phosphor particles exists in the epoxy once it has been cured.

Therefore, obtaining a uniform distribution of the phosphor particles within the epoxy is very difficult, if not impossible, due to the non-uniformity of the sizes of the phosphor particles. This inability to control the sizes of the phosphor particles and their locations within the epoxy results in difficulties in controlling the fraction of the primary light that is summed with the phosphor-emitted yellow light to produce white light.

Since this fraction cannot be precisely controlled, the quality of the white light produced by LED lamps may vary from one lamp to another, even for a given model manufactured by a particular manufacturer. Another disadvantage of this type of LED device is that the light emitting structure of the LED device is most efficient at emitting blue light in the range of approximately 450 nanometers (nm) to approximately 500 nm. There is reason to believe that LED devices may be developed in the future that will operate efficiently at shorter wavelengths, e.g., between approximately 400 and 450 nm. It would be desirable to provide an LED device that is capable of producing primary light at these shorter wavelengths and of performing phosphor conversion on the primary light to produce white light. However, mixing primary blue light of wavelengths below 450 nm with the phosphor-converted emission will not produce white light due to the fact that the wavelengths of the primary emission are hardly visible.

Accordingly, a need exists for an LED device that is capable of producing high quality white light through phosphor conversion of all of the primary light, and that is capable of being reproduced in such a manner that the quality and uniformity of the white light generated by the LED devices is predictable and controllable.

SUMMARY OF THE INVENTION

The present invention provides an LED device that is capable of performing phosphor conversion on substantially all of the primary light emitted by the light emitting structure of the LED device to produce white light. The LED device comprises at least

one phosphor-converting element located to receive and absorb substantially all of the primary light emitted by the light-emitting structure. The phosphor-converting element emits secondary light at second and third wavelengths that combine to produce white light. The second wavelength is greater than the first wavelength and the third wavelength is greater than the second wavelength. Secondary light at additional wavelengths may also be emitted by the phosphor-converting element. These additional wavelengths would also combine with the light of the second and third wavelengths to produce white light.

The phosphor-converting element generates the secondary light at the third wavelength in response to excitation by the primary light and/or the secondary light at the second wavelength. The excitation by the secondary light at the second wavelength is effected by macroscopic absorption and/or quantum-mechanical transfer. The phosphor-converting element includes either (a) a first host material doped with a first dopant and a second host material doped with a second dopant, which may or may not be the same as the first dopant, or (b) a host material doped with a first dopant and a second dopant. The first dopant emits the secondary light at the second wavelength and the second dopant emits the secondary light at the third wavelength. Furthermore, additional host materials and/or additional dopants that emit additional wavelengths of secondary light may be incorporated into the phosphor-converting element. These additional wavelengths of secondary light would be emitted by the phosphor-converting element in response to excitation by secondary light of the second or third wavelengths, or in response to excitation by the secondary light of one or more of the additional wavelengths. Secondary light of these wavelengths would then combine to create white light.

In accordance with an alternative embodiment, the light generated by the phosphor-converting element includes light at least one additional wavelength, which is generated in response to excitation by (a) the primary light and/or (b) the secondary light at any wavelength shorter than the additional wavelength. The phosphor-converting element generates the secondary light at the additional wavelength in response to excitation by (a) the primary light at the first wavelength, (b) the secondary light at the second wavelength, and/or (c) the secondary light at the third wavelength. Excitation by the secondary light occurs by (a) macroscopic absorption and/or (b) quantum-mechanical transfer. The secondary light of the second, third and the additional wavelengths combines to produce white light.

The present invention is not limited with respect to the types of phosphor-converting elements that are utilized in the LED device, or with respect to the composition of the phosphor-converting elements. The host material must be a phosphor compound that is capable of incorporating an atomically-dispersed dopant. The dopant must have a particular chemical relationship to the host that makes it suitable for being incorporated into the host. The host materials comprising the phosphor-converting elements may be, for example, phosphor-converting powders in an encapsulant (e.g., epoxy), phosphor-converting organic dyes, phosphor-converting substrates, phosphor-converting thin films, etc. Also, various combinations of these host materials and/or of the phosphor-converting elements can be created. In one case, an epoxy encapsulant is mixed with a phosphor powder. The phosphor-converting element may comprise a second host material that is a phosphor-converting thin film. In all cases, all of the primary light will be converted by one or more of the phosphor-converting elements such that virtually no primary light is left unused, or unconverted.

Other features and advantages of the present invention and variations thereof will become apparent from the following description, drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of the light emitting diode device that is suitable for use with the present invention.

FIG. 2 is a side view of the light emitting diode device of the present invention in accordance with a first exemplary embodiment wherein two phosphor thin films are utilized to perform the phosphor conversion necessary to produce white light.

FIG. 3 is a side view of the light emitting diode device of the present invention in accordance with a second exemplary embodiment wherein three phosphor thin films are utilized to perform the phosphor conversion necessary to produce white light.

FIG. 4 is a side view of a third exemplary embodiment of the light emitting diode device of the present invention, which corresponds to one possible modification of the light emitting diode device shown in FIG. 2.

FIG. 5 is a side view of a fourth exemplary embodiment of the light emitting diode device of the present invention, which corresponds to one possible modification of the light emitting diode device shown in FIG. 3.

FIG. 6 is a side view of the light emitting diode device of the present invention in accordance with a fifth exemplary embodiment wherein a phosphor-converting substrate

is utilized in conjunction with a phosphor thin film to perform the phosphor conversion necessary to produce white light.

FIG. 7 is a side view of the light emitting diode device of the present invention in accordance with a sixth exemplary embodiment wherein a phosphor-converting substrate is utilized in conjunction with two phosphor thin films to perform the phosphor conversion necessary to produce white light.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 is a perspective view of a light emitting diode (LED) 1 that is suitable for use with the present invention. However, it should be noted that the LED of the present invention is not limited to any particular LED. Those skilled in the art will understand that a variety of LED designs are suitable for use with the present invention.

For purposes of describing the typical components of the LED 1, the LED 1 has been shown without any phosphor-converting elements disposed thereon. The phosphor-converting elements of the present invention include, but are not limited to, phosphor-converting dyes, phosphor-converting powders in an encaspulant, phosphor-converting thin films, phosphor-converting substrates, as discussed below in more detail. Those skilled in the art will understand, in view of the discussion provided herein, how any of these types of phosphor-converting elements may be used to achieve the goals of the present invention. The phosphor-converting elements perform phosphor conversion by either macroscopic absorption or by quantum-mechanical transfer, both of which are know in the art. Quantum-mechanical transfer occurs between dopants that are not more than approximately 6 nanometers (nm) apart. Therefore, phosphor conversion via quantum-mechanical transfer will only happen under certain circumstances.

The LED 1 may comprise, for example, a light emitting structure 2, which comprises two n-GaN layers 3 and 4, an SQW or MQW GaInN layer 5, a p-AlGaN layer 6 and a p-GaN layer 7. The light emitting structure 2 also comprises an n-electrode bond pad 8, an n-electrode 3, a p-electrode bond pad 11 and a p-electrode 12. The n-electrode 3 is comprised of GaN and the p-electrode 12 is a light transmitting and current spreading material comprised of Ni/Au. The electrode bond pads 8 and 11, when connected to a voltage supply (not shown), provide the biasing current for causing the LED 1 to emit light.

The light emitting structure 2 is disposed on a substrate 13. The substrate material used will depend on the types of phosphor-converting elements incorporated into

the LED device and on the manner in which the layers of the LED device are arranged with respect to one another. The manner in which a suitable substrate material is chosen will be discussed below in detail. As stated above, the light emitting diode device 1 is not limited to any particular type of light emitting diode device, with the exception that the light emitting diode device utilized in accordance with the present invention emits a primary light that is either blue or ultraviolet (UV) and has a wavelength that is equal to or less than 460 nm, and preferably is equal to or less than 440 nm. Those skilled in the art will understand that various light emitting diodes are known that are capable of emitting light of this wavelength.

The light emitting structure 2 that generates the blue or UV primary emissions may be grown epitaxially on the substrate of the LED device 1. In some cases, the substrate material may be transmissive, whereas in other cases it may be opaque, as described below in detail. Those skilled in the art will understand that a plurality of substrate materials are suitable for these purposes.

FIG. 2 is a side view of the LED device of the present invention in accordance with a first exemplary embodiment. The LED device 20 comprises a substrate 13, which is transparent or transmissive, and a light emitting structure 2, which is disposed on a surface of the substrate. In accordance with this embodiment, the LED device 20 comprises two phosphor thin films 22 and 23. One of the thin films 22 is disposed on the surface of the substrate 13. The other thin film 23 is disposed on top of thin film 22. A reflective electrode 21 preferably is disposed on the surface of the light emitting structure 2. The thin films 22 and 23 may be deposited by a plurality of known methods. Phosphor thin films have been used primarily in the thin film electroluminescent display industry. Therefore, the manner in which phosphor thin films can be achieved is known. Several known techniques may be used for depositing the phosphor thin films such as, for example, electron beam evaporation, thermal evaporation, rf-sputtering, chemical vapor deposition and atomic layer epitaxy.

The method that is utilized for depositing the thin film may depend on the desired characteristics of the thin film. For example, if the thin film is to absorb all of the primary radiation emitted by the LED, one particular deposition technique may be used, whereas if the thin film is to allow a percentage of the primary radiation to pass through it, a different technique may be used. Those skilled in the art will understand which type of technique is to be utilized in order to obtain a thin film having the desired characteristics.

Preferably, the method for depositing the thin films 22 and 23 shown in FIG. 2 is rf-sputtering. In accordance with this method, phosphor powder is pressed into a target of a diameter slightly exceeding the LED wafer diameter such that homogenous coverage is ensured. As will be understood by those skilled in the art, the sputter gas characteristics can vary, but preferably the sputter gas is Argon and comprises approximately 1% to approximately 3% of oxygen, and the pressure and RF power input are matched to give optimum thickness and homogeneity. The distance between the target and the substrate preferably is approximately 5 to 10 cm. The phosphor powder preferably is a Cerium-doped Yttrium-Aluminum-Garnet ($Y_3Al_5O_{12}:Ce^{3+}$) compound, also denoted as YAG:Ce. However, those skilled in the art will understand that the present invention is not limited to using any particular type of phosphor for this purpose. Those skilled in the art will understand that a plurality of different types of phosphors exist that are suitable for this purpose.

The homogeneity of the phosphor thin films can be further improved by rotating the LED wafer on a particular trajectory, such as on eccentric circles, or more complicated trajectories. This technique of rotating the wafer to improve the homogeneity of a material is known in the art. Since the manner in which phosphor thin films having a desired homogeneity can be created and deposited is known, in the interest of brevity, no further discussion of the manner in which this is accomplished will be provided herein.

During operation, the light emitting structure 2 generates primary blue or ultraviolet (UV) emission. The primary emission. propagates through the substrate 13 and impinges on thin film 22. The thin film 22 converts some or all of the primary light impinging thereon into blue light of a wavelength that is larger than the wavelength of the primary light. The excitation of the thin film 22 that produces the blue light of the longer wavelength is effected by macroscopic absorption. The converted blue light is emitted by thin film 22. A portion of the blue light emitted by thin film 22 passes through thin film 23 without exciting the phosphor thin film 23. A portion of the blue light emitted by thin film 22 excites the dopants contained in thin film 23 and is converted into yellow light. Any primary light that was not converted by thin film 22 is also converted into yellow light by thin film 23. The yellow light emitted by the thin film 23 combines with blue light emitted by film 22 to produce white light.

It should be noted that the primary light may comprise light having more than one wavelength. Similarly, the light emitted in response to excitation by the primary light

may comprise light of more than one wavelength. For example, the blue light emitted by thin film 22 may correspond to a plurality of wavelengths making up a spectral band. Likewise, the yellow light emitted by thin film 23 may correspond to a plurality of wavelengths making up a different spectral band. Wavelengths of both of these spectral bands may then combine to produce white light. Therefore, although individual wavelengths are discussed herein for purposes of explaining the concepts of the present invention, it will be understood that the excitation being discussed herein may result in a plurality of wavelengths, or a spectral band, being emitted. Wavelengths of the spectral bands may then combine to produce white light. Therefore, the term "spectral band" is intended to denote a band of at least one wavelength and of potentially many wavelengths, and the term "wavelength" is intended to denote the wavelength of the peak intensity of a spectral band.

For good color rendering, i.e., in order to produce high quality white light, the blue light that is combined in the final summation to produce white light should include blue light of wavelengths shorter than approximately 480 nm. Since the primary light is converted into light of a longer wavelength than the primary light, the light emitting structure 2 should emit primary light at wavelengths shorter than approximately 440 nm. However, those skilled in the art will understand that the present invention is not limited to emitting primary light at wavelengths below 440 nm, but that it is preferable to do so in order to achieve all of the goals of the present invention, which include producing white light of the highest quality. Of course, high quality color rendering is not the only goal of the present invention. Other factors, such as design flexibility, costs, efficiency, etc., should be taken into account in designing and creating the LED device of the present invention. In some cases, it may be desirable to opt for lower color-rendering quality in order to maximize realization of one or more of the other goals of the present invention, as will be understood by those skilled in the art.

The amount and the spatial distribution of the dopants in the thin films can be controlled with great precision. By precisely controlling these characteristics of the thin films, the fraction of the primary radiation that will pass through the thin films without being converted is predictable and can be controlled. Therefore, the characteristics of the white light produced by the light emitting diode device 20 can be ensured. Thus, manufacturing uncertainties can be eliminated and LED devices having high quality and consistency can be obtained.

FIG. 3 is a side view of the light emitting diode device 30 of the present invention in accordance with a second embodiment. The LED device 30 is very similar to the LED device 20 shown in FIG. 2, with the exception that the LED device 30 comprises three phosphor thin films 25, 26 and 27, which function in a slightly different manner than the manner in which thin films 22 and 23 shown in FIG. 2 function. The techniques discussed above for depositing thin films 22 and 23 preferably are also used to deposit thin films 25, 26 and 27. Therefore, in the interest of brevity, a detailed discussion of the manner in which this can be accomplished will not be provided herein.

The thin films 25, 26 and 27 of the LED device 30 generate blue, green and red light, respectively. When the light emitting structure 2 is driven, the primary light propagates through the substrate 13 and impinges on thin film 25, which absorbs some or all of the primary light and converts it into blue light of a longer wavelength than the wavelength of the primary light. The converted blue light then impinges on thin film 26, which converts a portion of the converted blue light into green light.

A portion of the unconverted blue light emitted by thin film 25 passes through thin film 26 without being converted. Thin film 26 may also convert some or all of any remaining primary light into green light. Thin film 27 may be fabricated to convert either blue light into red light or to convert green light into red light. Therefore, either a fraction of the blue light emitted by thin film 25, or a fraction of the green light emitted by thin film 26 will be converted into red light by thin film 27. Any remaining primary light will also be converted by thin film 27 into red light. A portion of unconverted blue and green light will pass through thin film 27 and combine with the red light to produce white light.

FIG. 4 is a side view of a third embodiment of the present invention, which corresponds to a modification of the embodiment shown in FIG. 2. The reflective electrode 21 shown in FIG. 2 is not incorporated into the LED device 40 shown in FIG. 4. The substrate 15 may be, for example, Silicon Carbide (SiC) or a form of Aluminum Oxide (Al_2O_3) known as sapphire. The thin film 22 is disposed on a surface of the light emitting structure. The thin film 23 is disposed on thin film 22. The LED device 40 operates in essentially the same manner in which LED device 20 operates to produce white light. The primary light emitted by the light emitting structure 2 impinges on thin film 22. Thin film 22 converts some or all of the primary light impinging thereon into blue light of a wavelength that is longer than the wavelength of the primary light.

The converted blue light is emitted by thin film 22. A portion of the blue light emitted by thin film 22 passes through thin film 23 without exciting phosphor and, therefore, remains unconverted. A portion of the blue light emitted by thin film 22 excites the phosphor of thin film 23 and is converted into yellow light. Also, any remaining primary light is converted by thin film 23 into yellow light. This yellow light is emitted from the thin film 23 and combines with the portion of the unconverted blue light emitted by thin film 22 to produce white light.

FIG. 5 is a side view of a fourth exemplary embodiment of the present invention, which corresponds to a modification of the embodiment shown in FIG. 3. The reflective electrode 21 shown in FIG. 3 is not incorporated into the LED device 50 shown in FIG. 5. Also, the substrate 15 is may be identical to the substrate shown in FIG. 4. The thin film 25 is disposed on a surface of the light emitting structure 2. The thin film 26 is disposed on thin film 25. The thin film 27 is disposed on thin film 26. The LED device 50 operates in essentially the same manner in which LED device 30 shown in FIG. 3 operates.

The primary light emitted by the light emitting structure 2 impinges on thin film 25, which absorbs some or all of the primary light and converts it into blue light of a longer wavelength than the wavelength of the primary light. The converted blue light then impinges on thin film 26, which converts a portion of the converted blue light into green light. A portion of the unconverted blue light emitted by thin film 25 passes through thin film 26 without being converted. Thin film 26 may also convert some or all of any remaining primary light into green light. Either the blue light emitted by thin film 25 or the green light emitted by thin film 26 is then converted into red light by thin film 27. Fractions of unconverted blue and green light pass through thin film 27 and combine with the red light to produce white light. No primary light is contained in the final combination that produces white light, i.e., none of the primary light remains unused, or unconverted.

FIG. 6 is a side view of the light emitting diode device 60 of the present invention in accordance with a fifth exemplary embodiment. The light emitting structure 2 is disposed on a substrate 61, which preferably is a single crystal phosphor substrate, although other materials may be used for the substrate 61, as discussed below in detail. A reflective electrode 21, which may be identical to the reflective electrode 21 shown in FIGS. 2 and 3, is disposed on a surface of the light emitting structure 2. A single phosphor thin film 62 is disposed on a surface of the substrate 61.

The light emitting structure 2 preferably is grown epitaxially on the single crystal phosphor substrate 61. The substrate 61 preferably is a single crystal Cerium-doped Yttrium-Aluminum-Garnet ($Y_3Al_5O_{12}$:Ce^{3+}) compound. Substrates such as sapphire are typically used in LED devices because they have desirable thermal, mechanical and crystalline structure properties. Although Aluminum Oxide has the thermal, mechanical and crystalline structure properties that are needed for a suitable substrate, the lattice structure of this compound is too dense to allow it to be doped with rare earth ions, such as Ce^{3+}, in sufficient concentrations to enable it to perform phosphor conversion.

In accordance with the present invention, it has been determined through research and experimentation that a single crystal Yttrium-Aluminum-Garnet ($Y_3Al_5O_{12}$), commonly referred to as "YAG", also has the thermal, mechanical and crystalline structure properties that make it suitable for use as the substrate of an LED device. Since it is known that YAG can be doped with Cerium to produce a yellow-light-emitting phosphor, it has been determined, in accordance with the present invention, that a single crystal Cerium-doped YAG compound ($Y_3Al_5O_{12}$:Ce^{3+}) can serve the dual purpose of providing all of the necessary functions of an LED device substrate and of generating phosphor-converted emissions.

The substrate 61 luminesces yellow light in response to receiving primary light generated by the light emitting structure 2 of the LED, which is either blue light or ultraviolet light having a wavelength that is less than approximately 450 nm. Some or all of the primary light generated by the light emitting structure 2 that propagates into the substrate 61 is absorbed and is converted into yellow light. The unconverted primary light impinges on the thin film 62, which converts the primary light into blue light of a wavelength greater than 460 nm. The yellow light emitted by the substrate 61 then combines with the blue light to produce white light.

The characteristics of the substrate 61 are capable of being precisely controlled by precisely controlling the doping process. Thus, the fractions of light that are converted and that remain unconverted as the light passes through the substrate 61 and through the thin film 62 are predictable and controllable. This allows the quality of the white light produced by the LED device 60 to be predicted and controlled, which, in turn, eliminates manufacturing uncertainties and ensures that variations in the quality of the white light produced are minimized or eliminated.

The thickness and doping of the substrate 61 are tailored in such a manner that the substrate 61 allows precisely the amount of primary light needed for excitation of the thin

film 62 to pass through the substrate 61 without being converted into yellow light. Those skilled in the art will understand the manner in which the substrate 61 can be tailored to achieve the desired conversion. In accordance with this embodiment, the light emitted by the light emitting structure of the LED device 60 should be equal to or greater than approximately 400 nm because substrate 61 will not be excited by primary light of wavelengths below this range. Of course, substrates made of material that is excitable at wavelengths beyond this range may also be suitable for use with the present invention.

FIG. 7 is a side view of the LED device of the present invention in accordance with a seventh exemplary embodiment. The LED device 70 comprises a substrate 72, a light emitting structure 2 disposed on a surface of the substrate 72, a reflective electrode 21 disposed on a surface of the light emitting structure 2 and two phosphor thin films 73 and 74, overlaying each other and disposed on a surface of the substrate 72. The thin films 73 and 74 may be fabricated and deposited in the manner discussed above with reference to FIGS. 2-6.

As stated above, the primary light is either blue light or ultraviolet light having a wavelength that is proximately equal to or less than 460 nm. Some or all of the primary light that propagates into the substrate 72 is absorbed and is converted into blue light having a wavelength that is longer than the wavelength of the primary light. The converted blue light is emitted by the substrate 72 and impinges on the thin film 73, which converts a portion of the blue light emitted by the substrate 72 into green light. The thin film 73 may also convert some or all of any remaining primary light into green light.

A portion of the blue light emitted by substrate 72 propagates through the thin film 73 without being converted by the thin film 73 into green light. The green light and the unconverted blue light impinge on thin film 74. Thin film 74 may be designed to be excited by the unconverted blue light or by the green light. In either case, a portion of the green and blue light will propagate through thin film 74 without being converted. Any remaining primary light will be converted by thin film 74 into red light. A portion of either the blue light emitted by substrate 72 or the green light emitted by thin film 73 will be converted by thin film 74 into red light, which combines with the blue light and green light to produce white light.

It should be noted that all of the embodiments discussed above provide LED devices that are capable of producing high quality white light with predictability and controllability, even with primary emissions of relatively short wavelengths. It should be

noted that although it has been stated herein that the wavelength of the primary emission is less than or equal to approximately 460 nm, and preferably is less than or equal to 440 nm, the LED devices of the present invention are not limited to any particular wavelengths. Those skilled in the art will also understand that the present invention is not limited to the embodiments explicitly discussed herein. For example, although various phosphor-converting substrates were discussed above, these substrates may also be viewed as thick films. Therefore, the LED device of the present invention may comprise a typical substrate, such as a Silicon Carbide or sapphire substrate, which provides the typical functionality of an LED substrate, and one or more phosphor-converting thick films having the phosphor-converting properties of the substrates discussed above and shown in FIGS. 6 and 7.

Such thick films may also be used in place of the phosphor thin films in some or all cases. Of course, using thick films instead of thin films may increase the overall dimensions of the LED device. Also, the ordering of the phosphor-converting elements within the LED device may be different from that shown in FIGS. 2-7, as will be understood by those skilled in the art. Therefore, the order in which the phosphor-converting elements appear in the figures should be viewed as exemplary and/or as the preferred ordering. Persons skilled in the art will understand that other variations and modifications may be made to the embodiments discussed above that are also within the scope of the present invention.

CLAIMS

What is claimed is:

1. A light-emitting device for generating white light, the light-emitting device comprising:

a light-emitting structure that emits primary light of a first wavelength, less than 460 nm, when driven; and

a phosphor-converting element located to receive and absorb substantially all of the primary light emitted by the light-emitting structure, the phosphor-converting element emitting secondary light at second and third wavelengths that combine to produce white light, the second wavelength being greater than the first wavelength and the third wavelength being greater than the second wavelength, the phosphor-converting element generating the secondary light at the third wavelength in response to excitation by at least one of (a) the primary light and (b) the secondary light at the second wavelength, excitation by the secondary light at the second wavelength being by at least one of (a) macroscopic absorption and (b) quantum-mechanical transfer, the phosphor-converting element including one of:

(a) a first host material doped with a first dopant and a second host material doped with a second dopant, and

(b) a host material doped with a first dopant and a second dopant; the first dopant emitting the secondary light at the second wavelength and the second dopant emitting the secondary light at the third wavelength.

2. The light emitting device of claim 1, wherein the phosphor-converting element comprises a first host material doped with a first dopant and a second host material doped with a second dopant, the first host material including one of:

a substrate doped with the first dopant, a thin film doped with the first dopant, a phosphor powder mixed in with an epoxy, the phosphor powder being doped with the first dopant, and a dye doped with the first dopant.

3. The light emitting device of claim 2, the second host material including one of:

a substrate doped with the first dopant, a thin film doped with the first dopant, a phosphor powder mixed in with an epoxy, the phosphor powder being doped with the first dopant, and a dye doped with the first dopant.

4. The light emitting device of claim 3, wherein the first and second host materials are first and second phosphor thin films, respectively, and wherein the light of the second wavelength is blue light and wherein the light of the third wavelength is yellow light, the light of the second and third wavelengths combining to form white light.

5. The light emitting device of claim 1, wherein the phosphor-converting element is a host material doped with a first dopant and a second dopant, the first dopant emitting the secondary light at the second wavelength and the second dopant emitting the secondary light at the third wavelength, wherein the host material is a substrate.

6. The light emitting device of claim 1, wherein the phosphor-converting element is a host material doped with a first dopant and a second dopant, the first dopant emitting the secondary light at the second wavelength and the second dopant emitting the secondary light at the third wavelength, wherein the host material is a phosphor thin film doped with the first and second dopants.

7. The light emitting device of claim 3, wherein the host material includes one of:

a Yttrium-Aluminum-Garnet compound doped with Cerium, chemically defined as $Y_3Al_5O_{12}:Ce^{3+}$, a Yttrium-Aluminum-Garnet compound doped with Holmium, chemically defined as $Y_3Al_5O_{12}:Ho^{3+}$, and a Yttrium Aluminum-Garnet compound doped with Praseodymium, chemically defined as$Y_3Al_5O_{12}:Pr^{3+}$.

8. The light emitting device of claim 7, wherein a part of the Yttrium of the host material is replaced by one or more rare earth ions.

9. The light emitting device of claim 7, further comprising:

a light-transmissive substrate, the substrate having first and second surfaces, the light emitting structure being disposed on a first surface of the substrate, the first surface of the substrate being in contact with a second surface of the light emitting structure, the first and second host materials being first and second phosphor thin films, respectively, the first phosphor thin film being disposed on the second surface of the substrate, the second phosphor thin film being disposed on the first phosphor thin film, the light of the second wavelength emitted by the first thin film being blue light, the light of the third wavelength emitted by the second thin film being yellow light, the light of the second and third wavelengths combining to form white light.

10. The light emitting device of claim 7, further comprising:

a light-transmissive substrate, the substrate having first and second surfaces, the light emitting structure being disposed on a first surface of the substrate, the first surface of the substrate being in contact with a second surface of the light emitting structure, the first and second host materials being first and second phosphor thin films, respectively, the first phosphor thin film being disposed on the second surface of the substrate, the second phosphor thin film being disposed on the first phosphor thin film; and

a second phosphor-converting element, the second phosphor-converting element being a third phosphor thin film, the third thin film being disposed on the second phosphor thin film, the third phosphor thin film receiving light of one of the first, second and third wavelengths and converting a portion of the received light of one of the first, second and third wavelengths into light of a fourth wavelength, the light of the second wavelength being blue light, the light of the third wavelength being green light, and the light of the fourth wavelength being red light, the light of the second, third and fourth wavelengths combining to form white light.

11. The light emitting device of claim 9, further comprising:

a reflective electrode disposed on the first surface of the light emitting structure, and wherein primary radiation emitted by the light emitting structure that impinges on the reflective electrode is reflected by the reflective electrode toward the light emitting structure such that the reflected radiation is directed toward the substrate.

12. The light emitting diode device of claim 10, further comprising:

a reflective electrode disposed on the first surface of the light emitting structure, and wherein primary radiation emitted by the light emitting structure that impinges on the reflective electrode is reflected by the reflective electrode toward the light emitting structure such that the reflected radiation is directed toward the substrate.

13. The light emitting diode device of claim 1, wherein the first wavelength corresponds to a peak wavelength of a first spectral band, the second wavelength corresponds to a peak wavelength of a second spectral band, and the third wavelength corresponds to a peak wavelength of a third spectral band.

14. The light emitting diode device of claim 1, wherein the light generated by the phosphor–converting element includes light at at least one additional wavelength, the

light at the at least one additional wavelength being generated in response to excitation by at least one of (a) the primary light, (b) the secondary light at any wavelength shorter than the at least one additional wavelength, the phosphor-converting element generating the secondary light at the at least one additional wavelength in response to excitation by at least one of (a) the primary light and (b) the secondary light at the second wavelength and (c) the secondary light at the third wavelength, excitation by the secondary light being by at least one of (a) macroscopic absorption and (b) quantum-mechanical transfer, the secondary light of the second, third and the at least one additional wavelength combining to produce white light.

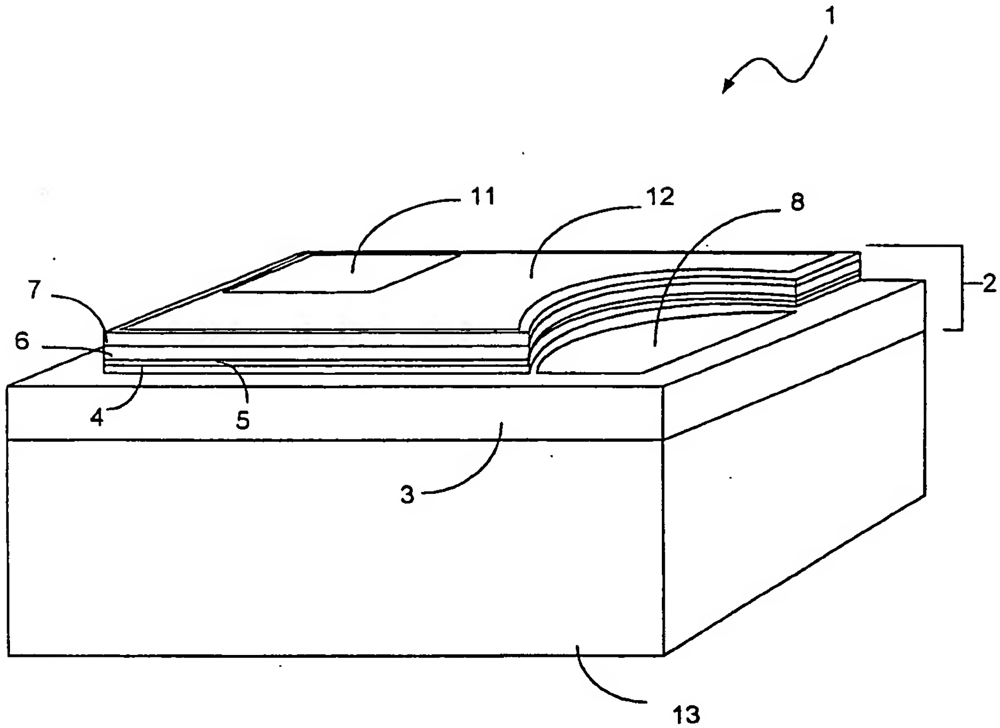


Fig. 1

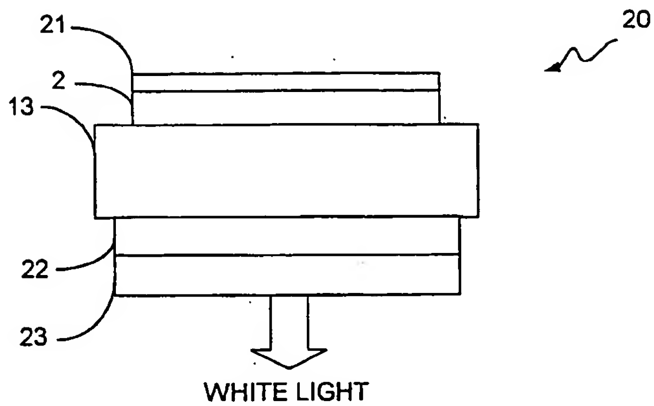


Fig. 2

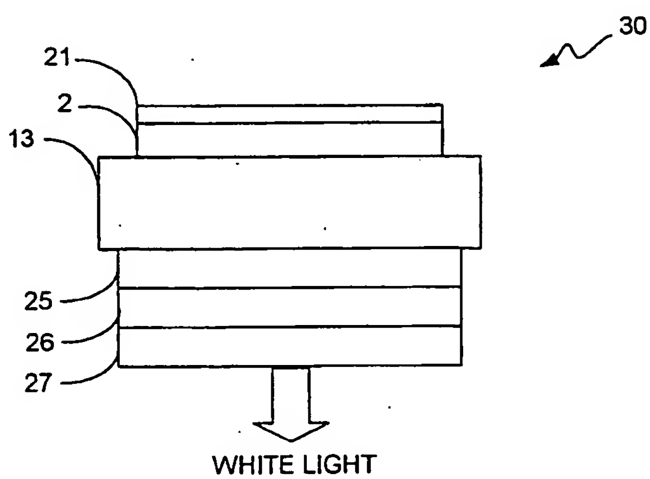


Fig. 3

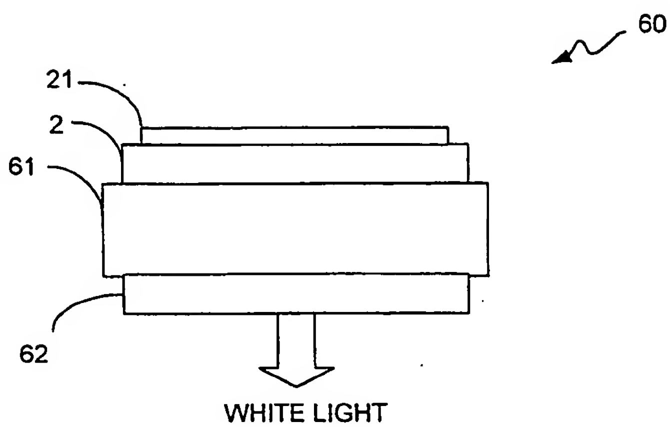


Fig. 6

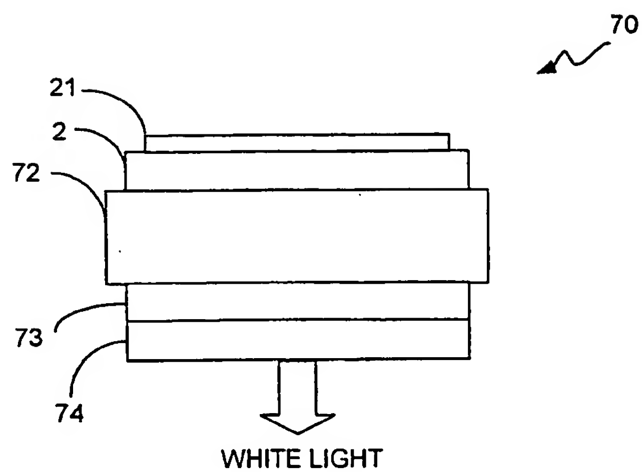


Fig. 7